On Cooperation In A Multi Robot Society For Space Exploration

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Abstract

Robot cooperation is a recently emerging field in robotics that aims for versatility, adaptability, robustness and low cost and is therefore of interest in various application areas. This paper tries to describe multi robot societies and how they may be useful in space exploration. Building on various simulation and theoretical results, a simple multi robot society (SMURFS) was built and used to test some of multi robot cooperation and reconfiguration algorithms. We outline future extensions currently in the works and our vision for the next iterations of the SMURFS society.

1 Introduction

Space exploration is nowadays mainly done by robotic agents, providing a cheaper and 'safer' way, compared to human exploration, to explore and return scientific data. In the new vision for space exploration speech by U.S. President Barack Obama, the focus of exploration in the coming years within NASA, was shifted towards asteroids, nevertheless the exploration of Moon and Mars and creation of a permanent manned base are still envisioned [20]. The plans of other agencies (e.g. JAXA[1] and ESA [24]) show the international commitment to space exploration. To be able to build these outposts advancements in technology and robotics need to be made, as robots will play an essential part in constructing the bases and assisting the human explorers. In fact in all these plans the need for robots that act as pre-cursor missions, as well as give assistance to the human explorers is highlighted. Therefore heterogeneous, interacting space agents (from satellites to rovers) will be developed and used in space exploration, but with the increasing amount of agents new problems arise.

One of the problems encountered is the delay of communications in space due to the vast distances, and increasingly, also the problem of bandwidth limitations, especially if more and more agents are used. This is very important for tele-controling these robots, so increased autonomy on space agents can greatly decrease this need for higher bandwidths and increase the operational time and therefore the scientific return of the missions [4]. Space agents usually have also limited mobility (e.g. a pre-defined amount of fuel or energy), communication (e.g. power), and size (because of the cost of launch per kg).

We think that a distributed approach, using multiple heterogeneous robots, is better suited because it can provide an extra level of flexibility and a high level of adaptability (e.g. reconfigurability). Multi robot systems can also increase the robustness, autonomy and the increase the overall chance of success. Though the use of multiple robots in a cooperative way, by itself, reaches technological limits because of the inherent need to cope with multiple, autonomous entities, they provide some very interesting advantages: the robots do not need to be as specialized, the risk is distributed between multiple agents, and the production costs per unit are decreased.

These systems can also be designed for lower reliability per agent and still provide more scientific return, because of the duplication. This is a trend often seen in space missions, which is shown by the following quote: "I could triple the cost of the project to try to guarantee success, or I could do three projects and, even if one fails, I get more done", [15] by Scott Horowitz, regarding the LCROSS mission, a comparably cheap Class D (i.e. high-risk) mission (in)to the moon.

We are describing a visionary scenario for planetary exploration using multiple, reconfigurable robots. These robots will be able to collaborate and cooperate in the unknown terrain and will act as an embodied, distributed artificial intelligence achieving common actions and goals, as specified by mission control to the society not a particular agent in it.

We propose a system of robots with an emerging intelligence due to the local interactions and following a global goal. These goals could be the distributed exploration, localization (of e.g. resources), construction (or generally preparation of the terrain) and also assisting the astronauts, by e.g. provide a distributed mesh-like wireless communications network to link astronauts with each other and mission control.

[1] http://www.kantei.go.jp/jp/singi/utyuu/tukitansa/dai7/siryou1.pdf

1.1 Multi Robot Space Exploration Scenario

The scenario selected here starts with a purely robotic exploration mission and shows how multi robot teams can increase the return of scientific data. As mentioned above robots will be sent as pre-cursors to human space exploration, to gather information and provide scientifically interesting data to scientists on Earth. Tasks for the robots will include mapping landing sites, constructing habitats and power plants, communicating with and acting as a communication relay to Earth. Scenarios such as these imply many different robots, with different, but overlapping, capabilities working together.

These autonomous systems can be used in various ways like forming groups dynamically together with an autonomous task distribution system to optimize performance. The robots themselves will optimize their travel-time, wait-time and the overall time-to-finish for a given task. The robots will be used for establishment of robotic science stations for continuous measurement and communications, construction of beaconed roadways and site preparation for human exploration, as well as, the deployment of human habitat modules.

Once a location for a (mainly self-sustaining) outpost is found, the robots are split into different groups, with each having a different task, including soil preparation and movement, carrying construction material (e.g. solar panels) in tight-cooperation. Meanwhile, other rovers will begin with the exploration and surveying of the region around the construction site. Mission Control (on Earth) can then together with the robots decide which areas are the most interesting for scientific research. Agents with specialized sensing instruments are sent to investigate and cover as much of the area as possible. Other agents will, while being in a formation, generate a wireless communication and emergency network for the robots, as well as, the human explorers. In this scenario the heterogeneity of the space agents is exploited throughout the whole mission to allow for better performance.

We aim to model the agents power constraints, i.e. robots have to reload at a base station in certain interval, and failures, e.g. they are destroyed or lost. The remaining units, after detecting the failure, should adapt their strategy to provide as much of the services as possible by changing their position (or maybe asking for reinforcements from the base station).

A similar scenario can be found in the Carnegie-Mellon university's FIRE Team proposal describing a "Heterogenous Multi-Rover Coordination for Planetary Exploration"[2].

Our scenario can further be extended to human-robot exploration teams, for example, to search cooperatively for a location suitable in size and other properties to harbor a permanent human settlement.

[2]http://www.cs.cmu.edu/~fire/

2 Related Work

Multi robot systems have been of interest to researchers for a long time, for example there already were plans for (fully) autonomous factories [9], various military projects [18] and space exploration robots decades ago. The topic has become more and more interesting over recent years and an increasing amount of research is done today in the field of robot cooperation.

A good summary, with reasoning for choosing multi robot systems over a single robot, can be found in [6]. In essence, the main reasons are usually [16, 1, 2]: dealing with more complex tasks; broader spectrum of capabilities; greater flexibility; more error prone and added expendability (just to name a few).

The work presented in this paper builds on previous research done in the area of robotics such as reconfigurable, multi robot, distributed, self learning systems such as the ones described in [13] and [12]. These were the cornerstones of the SMURFS robot society, which was born out of these two theses. The project then started to evolve to its current state and is expected to eventually turn into a platform where new algorithms and approaches in related areas can be developed and tested.

There are some other platforms with similar goals such as the Centibot [11] framework that aims to aid in the development of large scale robotic multi-agent systems, as well as, the SWARM [23] project, which aims to deploy a highly redundant underwater monitoring systems using multiple, homogeneous, autonomous underwater robotic probes. The SUBMAR robotic society that monitors liquid processes, as described in [22] is another example of multiple cooperative robots. Recently the EU funded Swarmanoid project has been focusing on swarms and heterogeneous robot societies based on a previous version of it that was homogeneous. It currently tries to generate self organizing groups of heterogeneous robots as described in [21].

For the future we are also looking into swarm intelligence, which combines the research in multi robot cooperation and artificial intelligence to produce simple agents that by working together can solve rather complex tasks. It is currently a research topic within the Advanced Concepts Team (ACT) of the European Space Agency [17].

3 Project SMURFS

To solve some of the problems and test the abilities of current algorithms a multi robot society was implemented in the project SMURFS (Society of MUltiple Robots For Space), which started in 2009 with two theses done in cooperation at the Helsinki University of Technology, the Lulea Technical University and the University of Tokyo. It consists of a prototypical robot society, built from LEGO

Mindstorms and aiming to be a cost-efficient framework for multi robot research (with emphasis on reconfigurable robotics); and a simulator, implemented for development and testing of multi robot cooperation strategies. A first version of the society, consisting of four robots, and a basic control algorithm were demonstrated at the 'Eighteenth Annual Robot Exhibition' during IJCAI 2009.

4 The Robots

The system is comprised of four homogeneous units that form a chain/tree society that moves in the horizontal plane, this is, the units will drive around in the floor and reconfigure themselves by driving around each other and linking to create different shapes in two dimensions. The robots are shown in Figure 1. A detailed description of the first generation of the SMURFS robots is found in [12].

4.1 The Mechanics

The units in the system are mostly made out of LEGO Mindstorms NXT technology, including the main controller unit, sensors, actuators and a set of LEGO pieces that are used to create the mechanical structures. An expansion board was also developed to add some external electronics and expand the capabilities on the LEGO NXT system by adding a servo motor and 7 LEDs to be detected by the LEGO Mindstorms light sensor.

4.2 The Motion System

In this prototype a novel motion technique was developed using a single actuator for traction and two actuators to both steer the driving direction and change the orientation of the outer structure independently. This enables two or more units to be attached to each other and to steer their individual motion systems without putting any kind of stress on the link, avoiding any undesired change in the orientation of the joint structure that could occur while steering the individual motion systems. Units are also able to disable their motion system to let other units do the driving and save batteries without interfering or resisting the overall movement of the joint structure.

4.3 The Expansion Board

As the NXT brick can only connect up to 3 actuators through its output ports and up to 4 sensors as inputs an Expansion board, to broaden these constraints was developed using the ATMega164P micro controller. It is has an I2C bus to be able to connect to the NXT, as well as 32 programmable I/O lines, real time clock, six PWM lines, two serial UARTS, analogue comparators, and many other features that make it suitable to expand the current capabilities of the robots.

5 The Software

5.1 Simulator

The software side, the SMRTCTRL simulator (shown in Figure 2) was developed specifically for the SMURFS project. It provides an easy way to implement and test various multi robot control algorithms. It is designed general enough to provide feasible simulation of various formation control algorithms in a lunar-surface-like environment. It can also be used to test other components of a multi robot system, like e.g. path planning, task sharing or multi-agent architectures, as well as, the reconfiguration control. An overview of the first implemented version of the simulator can be found in the Appendix of [13].

Figure 1. The SMURFS robots on-display at the IJCAI 2009 robotics exhibition.

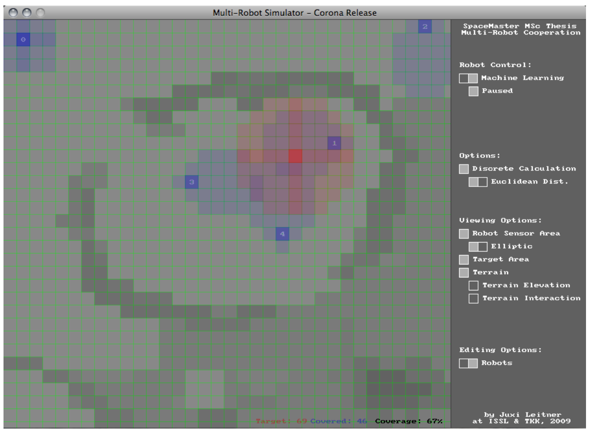

Figure 2. The SMRTCTRL simulator for testing algorithms and controlling the actual robots via Bluetooth.

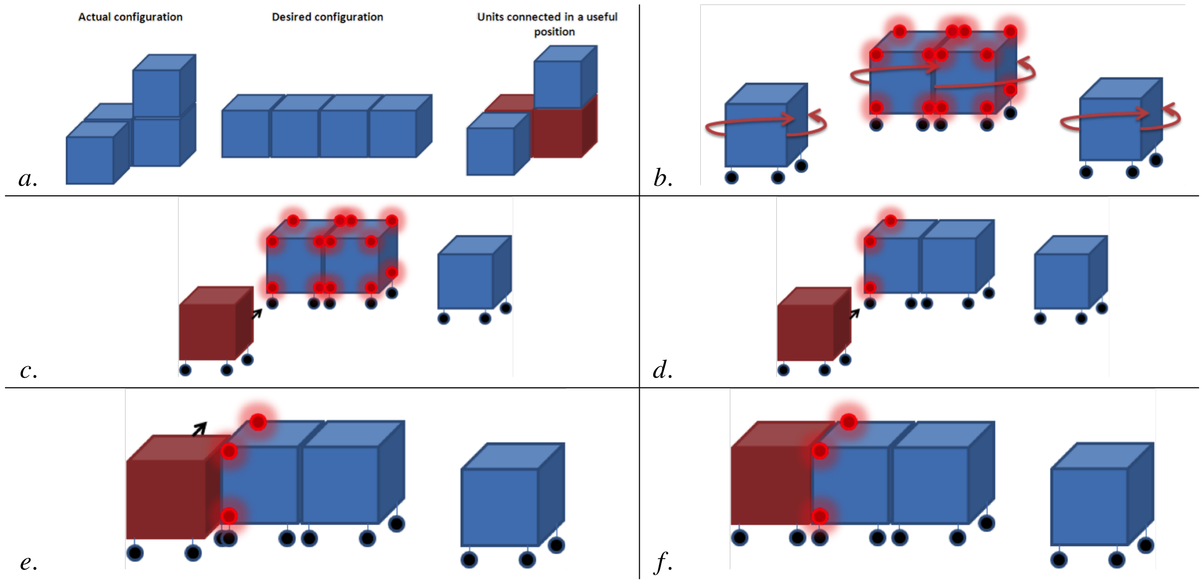

Figure 3. The reconfiguration control schematics for assembling the robots into a different structure.

5.2 Reconfiguration Control

The society here is defined as a group of robots working in a designated area that will discover the existence of more units of the same kind and try to communicate with them in order to work together. As this society needs to have a temporal leader to coordinate all the units while working towards the goal, an algorithm to designate a leader among the units present in the working area was developed. As a free or master unit discovers other units close to it, it will connect to the first on its discovery list and check the working status. The unit is either already working for another master unit, leading some units towards a task (is a master) or operating alone. Depending on this status the asking unit will then either become master or slave of the newly discovered unit (or none in special cases). This is further explained in [12].

Assembly. To get the units into the desired configuration, the master unit will direct all the needed units until the final structure is completed. To achieve this is will follow these steps (shown in Figure 3):

a. Check if there are units connected in a useful position regarding the desired configuration, retain them and order the rest to detach.Prepare the main structure to be able to rotate around its axis, taking into consideration the number of units and wheel coordination.

b. Turn on all LEDs and start rotating, while all free units start looking for a light source, by also rotating.

c. When one senses the right value in light intensity it stops moving and aligns itself to the main unit. Meanwhile, all other units are ordered to rest.

d. The main structure will turn off all except one LED, indicating the place where the candidate unit should be attached. The master will rotate until the light is again detected.

e. The master unit orders the now aligned unit to start approaching the main structure.

f. When in position the unit will be ordered to hook into the main structure by grasping the connection point.

The process will repeat until the structure is ready.

5.3 Formation Control

The cooperation between the robots was, at first, done for the simple case of formation control, for which two cooperation strategies were implemented in the SMRTCTRL simulator. For this we added a neurocontroller evolved with an organizational learning oriented classifier system (OCS) based approach, which will allow to increase the robustness of the robot control, compared to the first implemented simple vector-based (potential field) approach.

5.3.1 Simple Vector-based Control

The vector-based method uses attractive and repulsive forces, represented by vectors, to control the cooperation behaviour of the robots. The vectors are a sum of the (i) distance to the midpoint of the society (attractive), (ii) distance to close neighbors (repulsive) and (iii) distance to the midpoint of the target area (attractive). The added up vector generates a movement for each robot and the coverage optimization is an emergent property of this algorithm (mainly based on vector element (iii)).

5.3.2 Organizational-learning oriented classifier system (OCS)

OCS takes an organizational learning approach to machine learning, by adapting multi-agent systems. The method is described as “learning that includes four kinds of reinterpreted loop learning” [19] and tries to generate a hybrid genetic algorithm with the aim of overcoming the specific restrictions of the Michigan and Pittsburgh approaches [5]. The OCS system is a variant of a learning classifier system (LCS) (proposed by [7]) and uses reinforcements and evolutionary learning to select specific actions based on the state of the environment. We used this algorithm to position the robots for increased area coverage. The system consists of autonomous agents, with local implementations able to recognize the environment and its local state with the ability to change by executing an action.

Each agent has its local memory, which is used to create, store and update rules, also called classifiers (CFs). These rules are used to select the most suitable action for the current environmental state sensed. The agents apply reinforcement learning (RL) and genetic algorithm (GA) techniques to manage the rules (per agent). Each agent updates its rule-set and at certain intervals exchanges some rules with another agent. The specific implementation used here is described in detail in [14].

5.4 Localization

Gargamel, a visual tracking system implemented using a webcam and the open-source *reacTIvision* [10] system employing fiducial markers on top of the robots. The overhead camera provides positioning information to the robot controller (as an extension to the simulator).

5.5 Current Work

The aim of the current work is to extend the cooperation behaviours and abilities to provide more robust area coverage with more realistic constraints than in the first implementation. For this purpose, random breakdowns of the robots are introduced, while the robots should still provide coverage. For this we also aim to extend the simulator functionality, especially with regard to the discretization of positioning data and movements. A non-strictly discrete simulator will allow for better control of the robots and better implementation of the Gargamel system, this was seen as a necessary step after the presentation of the robots and simulator.

To allow a testing of the reconfiguration control purely in the simulator a more detailed modelling of the robots (with respect to the gripper and structure) is currently designed and implemented. Firstly, the already used reconfiguration algorithm is being tested within the simulator to test the simulator extension functionality and also to fine-tune the control mechanism.

6 Future Work

In the future we would like to add other ideas and coverage strategies for the case of distributed coverage. Examples could be taken from biological models, e.g. plant roots for MAS [8], and even from other space areas like satellite wireless sensor networks [25], where focus was put on the adaptability of the formation control.

Another direction that needs work on is robot localization, which right now is done by an overhead webcam (‘birds-eye-view’). We aim for implementing a distributed localization, probably based on current SLAM strategies, or an implementation using another genetic algorithm [3].

The continuing work on the SMURFS project, where we aim for a more flexible and robust system that adapts to the environment and to changes in the composition of the team. These changes could be unexpected, as for example, the failure of a robot, or expected, as, for example, due to the need for recharging the robots. With these more restrictive constraints, we want to generate a greater need for further cooperation between the robots.

Future work will try to explore a more heterogeneous configuration of the robots, by, for example, introducing multiple tasks to do for the robots, which then autonomously decide how to split into sub-groups performing these tasks, while adding fault tolerance and robustness to the mission. One could imagine that a society should, at the same time, try to give support to astronauts but also, with the remaining capacities, search for “points of interest” (e.g. rocks, craters,).

Another area for future work is to extend the scenario towards a more human-robot interaction based one, as already described above. In this case the robot team will be used to provide support (e.g. in comms) to the astronauts.

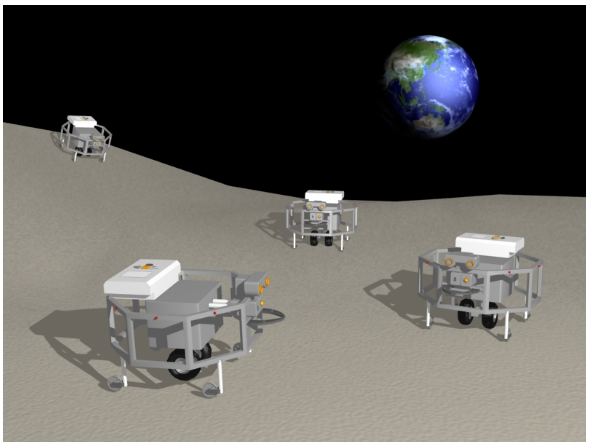

Figure 4. Artist’s impression of the SMURFS during lunar exploration.

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